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APPLICATION OF THE QSDC PROCEDURE TO THE FORMULATION OF SPACE SHUTTLE DESIGN CRITERIA

VOLUME I. STUDY EFFORT

by

Innes Bouton
Gary L. Martin

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FOREWORD

This report was prepared by Technology Incorporated under Contract NAS8-26918, the "Establishment of Statistically Based Criteria for Determining the Probability of Structural Failure," for the George C. Marshall Space Flight Center of the National Aeronautics and Space Administration. The work was administered under the technical direction of the Astronautics Laboratory of the George C. Marshall Space Flight Center.

All work was conducted at the Information Systems Division of Technology Incorporated, 3821 Colonel Glenn Highway, Dayton, Ohio, 45431, from 13 April 1971 to 13 March 1972. Mr. Innes Bouton was the Program Manager and Principal Investigator under the administrative guidance of Mr. Dudley C. Ward. The results of this study have been documented in this final report, identified as Technology Incorporated Report No. 425-72-14.

This report has been reviewed and is approved.

Dudley C. Ward
DUDLEY C. WARD
Manager,
Aeromechanics Department

ABSTRACT

As documented by a two-volume report, criteria to determine the probability of aerospace structural failure were statistically established according to the Quantitative Structural Design Criteria by Statistical Methods, the QSDC procedure. Since an Application Guide is needed to use the QSDC procedure, most of the study was directed to the development of this guide. Most of the considerations followed in the development of the Applications Guide and the Guide itself are covered in Volume II; the others are reported in Volume I.

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1. INTRODUCTION

The study to establish statistically based criteria for the probability of failure was directed to the development of the proposed structural design criteria method, the QSDC Procedure, as a means to establish the space shuttle structural design criteria. The proposed method, defined in an earlier report by the author, "Quantitative Structural Design Criteria by Statistical Methods" (AFFDL TR-67-107, Reference 1), was developed as a criteria method for aircraft systems. However, the concepts on which the QSDC Procedure are based are not restricted to aircraft systems but are univeral in scope and, therefore, should be equally applicable to the space shuttle. These basic concepts of the QSDC Procedure have been outlined in the "Summary of the QSDC Procedure for Space Shuttle Applications" (TI-425-71-4, Reference 2) and are briefly repeated here:

The QSDC Procedure is a failure-prevention criteria method in which failures may be of two types: understrength and overload. Each type of failure is prevented by designing for a specific design condition. Understrength failures are prevented by designing for the Limit Condition and overload failures are prevented by designing for the Omega Condition. To insure that the structure is properly designed for the Limit and Omega Conditions, the loads that correspond to these conditions are multiplied by a design factor. This factor is necessary to prevent failures that would occur if the structure were designed to sustain the loads at the Limit and Omega Conditions without consideration of the scatter in strength of the design. The design and test factor of safety (TFS) of the QSDC Procedure is defined in terms of the scatter in strength of the design and, therefore, fulfills the above purpose; whereas the discrete 1.5 factor of safety of the Present System cannot account for the strength scatter.

Reality dictates that failures cannot be absolutely prevented, and therefore, the definition of the prevention of failure must be tempered to reflect this. Such a tempering might be embodied by considering the probability of failure instead of considering the failure as a deterministic event. In the QSDC Procedure this is considered. Thus, the structural design criteria (the definition of the Limit and Omega conditions and the determination of the design factors) have been placed on the basis of a probability of failure analysis. As a result, the QSDC Procedure can specify criteria values that are deterministic in value yet are statistically based (on this probability of failure analysis).

The QSDC Procedure is, therefore, a method by which structural design criteria can be determined on the basis of the consideration of failure. What remains as the objective of this study is to relate this procedure to the design problems of the space shuttle and to clarify the implementation of the procedure

in solving these design problems. The design problems that are particularly those of the space shuttle and therefore needing attention are:

1) Thermal effects due to exit and re-entry

2) Utilization of advanced materials and structural concepts

These considerations are discussed in Section 2, The Study Effort. Other topics relating to the utilization of the QSDC Procedure in general that were not discussed in Volume II are presented in Section 3. The conclusions reached as a result of the study effort are discussed in Section 4. Recommendations for future effort in the application of the QSDC Procedure to the space shuttle structural design criteria, as well as to the development of the QSDC Procedure itself, are presented in Section 5.

2. STUDY EFFORT

2.1 Scope

The effort on the study to establish statistically based criteria for determining the probability of structural failure was divided into four phases and subdivided into eight study tasks. The four phases were:

1) Summary of Criteria Concepts
2) Review of Previous Programs
3) Applications to Space Shuttle
4) Final Report

Phase 4, the final report, of which this report is the end product, was not considered as a study phase. The following eight study tasks, therefore, apply only to the first three phases of the study:

1) Prepare Summary Report
2) Review Previous Criteria
3) Define Relation to Mission Requirements
4) Evaluate Program Success
5) Compare Space Shuttle Mission Requirements
6) Determine Changes in Criteria for Space Shuttle Criteria
7) Develop Examples
8) Prepare Application Guide

Essentially, the problem could be viewed as the definition of structural design criteria by a statistical analysis of the probability of failure. The means to solve this problem had been defined in Reference 1 as the QSDC Procedure. However, the QSDC Procedure needed to be developed before it could be utilized in the criteria definition for the space shuttle. This development has been included in the content of the Applications Guide (Task 8).

2.2 APPROACH

The definition of structural design criteria by a statistical analysis of the probability of failure has been outlined in Reference 1 as the QSDC Procedure. In the same report, an evaluation of other probability of failure (reliability) methods was made. The result was that they do not provide discrete design criteria and, therefore, are not practical design criteria methods. On the other hand, the discrete factor of safety methods which do not consider statistical variations, such as the Present (1.5 factor of safety) System, do not reflect the design requirements for the actual situation of the structure. The study concluded that a hybrid design criteria method was needed. As a result, the QSDC Procedure was developed as a criteria method that establishes criteria on a statistical (probability of failure) analysis that are deterministic in their utilization.

The QSDC Procedure, as developed in the content of Reference 1, was based on the evaluation of a present aircraft system, the F-100 century fighters. As a system that is already developed and in use, the F-100 reflects a utilization of the QSDC Procedure that is greatly different from an application to a new, undefined design. Essentially, the difference is that in the case of the F-100, the structure is known and the spectrum of operational conditions is known whereas in the case of the new design, neither the structure nor the operational condition spectra are known with a great degree of certainty. As a result, there has been a shift of emphasis in the utilization of the QSDC Procedure: from the knowledge of the structure (and therefore the strength scatter) and the operational condition spectra (and hence the design condition levels of Limit and Omega Conditions) as in the F-100 study to the estimation of the strength scatter and design conditions in the space shuttle study. This new emphasis has been included in the Applications Guide.

After the QSDC Procedure was developed to handle the above problems of a new design, it was applied to the Space Shuttle and example problems were developed to illustrate the use of the QSDC Procedure in this "new design" context. These were also included in the Applications Guide.

2.3 LIMITATIONS

The scope of this study was limited due to the time available. With respect to time, the criteria considered relative to the probability of failure were restricted to the structural design criteria and, in particular, the definition of the design conditions and the appropriate design factors. From the definition of failure as the catastrophic failure of the structure, no consideration of a yield strength requirement was made in this study. However, a discussion of potential future considerations for yield strength requirements can be found in Section 3, Related Topics.

2.4 DISCUSSION

As mentioned in the introduction, the QSDC Procedure was developed in Reference 1 relative to the static strength situation of a developed aircraft system, the F-100 series fighters. In this study, the utilization of the QSDC Procedure as a design criteria method for a new, unprecedented structure is contemplated. As a result, the QSDC Procedure must be adapted to the new frame of reference.

The basic concepts of the QSDC Procedure are not altered; rather, the scope of their application is expanded. In this study, an application of the QSDC Procedure to the development of structural design criteria for the space shuttle design problems is presented. In the following sections, the design problems and an approach to these design problems are outlined.

2.4.1. Thermal Effects

The first of the design problems not previously encountered by the QSDC Procedure are the thermal effects induced by the aerodynamic heating of the vehicle. Aerodynamic heating occurs in both the ascent and re-entry phases of the space shuttle mission and produces two thermal effects: elevated temperatures and temperature gradients. The QSDC Procedure, as a design criteria method, is required to specify in some manner design criteria that will effectively consider the effects of the aerodynamic heating in the design of the structure.

The general procedure of the QSDC is to define the operational condition that produces the critical loading on the structure, specify design levels (Limit and Omega) for that condition, and then design the structure for "no" failure at Limit and "most" survive Omega. In the case of aerodynamic heating, the thermal effects of temperatures and temperature gradients are the environmental conditions, but they do not fall in the category of operational conditions. (Essentially, they do not satisfy the requirement of defining an interface between the structural and non-structural organizations that would define corrective action.) Instead, the thermal effects can be viewed as derived conditions; that is, they are produced by the combination of a set of operational conditions. The thermal effects (TE) are a function of the general trajectory parameters, velocity (V) or mach number (M), altitude (h), vehicle orientation (α), and time (t); i.e.,

$$T.E. = f\ (M, h, \alpha, t)$$

As such, the thermal effects can be effectively controlled by controlling these trajectory parameters. The trajectory parameters can, therefore, be defined as the operational conditions, for they can fulfill the function of a meaningful interface between the non-structural control system and the structural system. As interface conditions, exceedances of specified design values (Limit and Omega Conditions) can be detected and corrective action taken. Instrumentation is required to detect any such exceedances and, therefore, should be considered in the determination of operational conditions. The trajectory parameters, M, h, α, t, are typically instrumented variables and therefore are easily defined as operational conditions.

The next step in the general procedure requires that the QSDC Procedure define the operational condition spectra and specify from it two design conditions (Limit and Omega). In the case being considered, the spectra of the trajectory parameters can be described as the combination of the individual trajectory parameters in a base-line trajectory described by the set (M, h, α, t) plus the dispersions of the individual trajectory parameters about the baseline values. That is, the spectrum can be defined by the set of points defined by:

$$(M + \Delta M,\ h + \Delta h,\ \alpha + \Delta\alpha,\ t + \Delta t)$$

where ΔM, Δh, $\Delta\alpha$, Δt are controllable by the non-structural systems. The magnitudes of ΔM, Δh, $\Delta\alpha$, and Δt that can be tolerated will define the Limit and Omega Conditions. Refer to Volume II for the definition of Limit and Omega Conditions in the QSDC Procedure.

The last general step of the QSDC Procedure is the design of the structure for the design conditions. The considerations to be made in the structural design that result from the effects of aerodynamic heating are the decrease in the strength of materials with elevated temperatures, thermal stresses resulting from temperature gradients, and creep due to repeated load and temperature combinations. It is recommended that these considerations be handled in the following manner:

The reduction in mean strength is interpreted as an increase in the strength scatter (γ_s) of the structure in the QSDC Procedure. The design of the structure therefore will require slightly larger design factors than the room temperature case. The design factor is applied to the load and matched with the allowable stress at elevated temperatures by adjusting the required area of the component. Usually, this will result in an increase in the area because of the larger design factor and lower allowable stress level. The structure is sized so that the probability of failure of the structure at the elevated temperature will be no greater than intended. Because the temperatures are the result of the trajectory, the loads that are considered in conjunction with the strength reduced by the temperature levels (which are used to define the reliability of the structure) may be more narrowly defined than the same combinations in the level flight phase. This would result in more realistic reliability calculations. However, the variation in the temperature-load combinations should be considered at all the points on the trajectory.

The second thermal effect to be considered is thermal stresses that result from temperature gradients. The QSDC Procedure can account for this effect in the load-condition context where the load is the mechanical stress induced by the thermal gradient stresses and the conditions are, again, the trajectory conditions. Similar to the loss of strength due to elevated temperatures, the mechanical loads that occur due to thermal stresses may be a narrowly defined distribution due to the trajectory dependancy; however, the variations in thermal stress and mechanical load at all points on the trajectory should be considered.

The third thermal effect to be considered is the effect of creep. The time dependent problem of creep would include detrimental deformations, creep cracking, and creep rupture. Of the three, creep rupture will contribute directly to failure and should, therefore, be given consideration in the residual strength function where elevated temperature environments are

encountered. Creep rupture may occur as the result of either an excessive load-time environment on the structure for the temperature encountered or a normal load-time environment on a structure weakened by creep cracking. If these mechanisms can be analyzed, they should be included in the probability of failure analysis. The problem of detrimental deformation is not included in the probability of failure analysis for the same reason that yield is not included (see Section 3). Essentially, detrimental deformations are correctable non-catastrophic failures, and can be accounted for by other (economic) considerations.

2.4.2 Advanced Materials and Structural Concepts

Advanced materials and structural concepts are particularly adaptable to the QSDC Procedure because the strength scatter (γ_S) of the structure depends on the γ_S in both the material and the structural concept. After appropriate testing has defined the γ_S in an advanced material and its structural configuration, the QSDC Procedure can utilize the material in a design much faster than is now possible. Where the Present System requires years of experience to determine the γ_S of an advanced material with a high level of confidence before it will utilize such a material for an aircraft structure, the QSDC Procedure can readily do so since it can include materials with a large γ_S.

Although larger factors of safety will result from materials with larger γ_S, such factors may be more than offset, especially when high-temperature strength is gained. For example, consider a conventional material A and an advanced material B. Material A has an γ_S of 0.04 at 70° F and an F_{tu} of 72 ksi at 70° F which is reduced 50 percent (36 ksi) at 600° F. Since $\gamma_S = \sigma/\mu$, σ may be kept constant as μ decreases (represented by an F_{tu} decrease) with temperature increase so that γ_S equals 0.08 at 600°F. Consequently, the LTFS for material A at 70° and 600° F is 1.25 and 1.62, respectively. Material B has an 0.08 γ_S at 70°F and an F_{tu} of 72 ksi at 70°F which is reduced only 16.6 percent (to 60 ksi) at 600°F. At the elevated temperature, material B has a 0.096 γ_S.

Standard design methods may be used to compare the two materials, i.e., the area (A) for a given load (P). First, a design load (P_D) is specified by multiplying the given load P by a design LTFS:

$$P_D = P \cdot LTFS$$

Second, the structure is sized by matching P_D to A:

$$P_D/A = \sigma_{all}$$

such that the allowable stress (σ_{all}) is equalled. Thus, for material A,

$$A_A = (LTFS_A \cdot P)/\sigma_{all_A} = 1.62P/36 = 0.045P$$

and for material B,

$$A_B = (LTFS_B \cdot P)/\sigma_{all_B} = 1.82P/60 = 0.0304P$$

The factor $(LTFS/\sigma_{all})$ thus defines the area/load ratio of the material. By comparing the required areas for the two materials and the material densities, the required weights of the two materials can also be compared and weight tradeoffs may be made. The required area for material B is 33 percent less than that for material A, even though material B has a greater LTFS. Assuming that the densities of the two materials are equivalent, material B would be lighter than material A. Consequently, material B has the advantage since its larger F_{tu} at the required temperature more than compensates for its higher LTFS; moreover, since the larger LTFS is based on a constant reliability level (see Figure 6, Volume II), the use of material B does not jeopardize the safety of the vehicle.

2.5 Redundant Structure

As the space shuttle structure, both booster and orbiter, is a highly redundant structure, the contribution that redundant structure makes to the probability of failure of the overall structure should be considered. Before this consideration can be made, however, the definition of the failure of redundant structure must be determined. This is discussed in Section 2.5.1. Once failure is defined, the modes of failure may be investigated, and finally the probability of that failure may be determined. Having thus established the probability of failure of redundant structure (Section 2.5.2), the effect of variations in margin of safety, tests, periodic inspections, fatigue measurement techniques, and replacement-refurbishment procedures on the probability of failure, and, hence, the reliability of the structure are discussed (Section 2.5.3).

2.5.1 Failure in Redundant Structure

Failure, in the context of this study, is the catastrophic rupture or collapse of the structure. This definition applies to both redundant and non-redundant structure in the sense that the end result--the loss of the overall structure and the inability to complete the mission-- is the same for both types of structure. However, failure in redundant and non-redundant structures are differentiated by their mechanisms. Failure in non-redundant structure is typically a single discrete event (the parting of metal), whereas failure is redundant structure is the result of the accumulated loss of redundancy through fatigue cracking and is culminated in the static failure of the weaker, remaining structure. In either case, the

final failure results from a load which exceeds the available strength of the structure. It is on this point, the load exceeding the available strength, that this study focuses its attention.

The externally applied load is assumed as known, at least in terms of a load spectrum with a probability distribution assigned to it. However, difficulty is encountered in the distribution of this external load among the elements of the redundant structure (to be discussed in Section 2.5.2). The strength of the redundant structure presents a similar difficulty. The determination of the probability of failure of a redundant structure as a function of the fatigue loading is a difficult, if not impossible, task.

2.5.2 Probability of Failure

The determination of the probability of failure of the redundant structure in the scope of this analysis requires the determination of the probability of exceeding a given load and the determination of the probability of exceeding the strength of the structure with that particular load. Unfortunately, neither of these probabilities is easily determined.

As previously mentioned, the mode of failure in redundant structure is the accumulated loss of redundancy and strength due to fatigue cracking of the structure. The analysis of the probability of failure should, therefore, be modeled after the mode of failure. That is, the probability of failure of each redundant element must be analyzed and combined in the determination of the probability of failure of redundant structure. Before such a modeling can occur, the following assumptions must be recognized and considered in the analysis:

1) Separate, non-redundant elements or load paths can be defined within the redundant structure.

2) The distribution of the externally applied loads among the elements of the redundant structure can be calculated.

3) The redistribution of the externally applied loads with each element failure can be calculated.

4) The strength distribution of each element as a function of the loading history can also be calculated.

These assumptions are necessary for an element-by-element analysis of the probability of failure of a redundant structure. Obviously, if the redundant structure were considered as a black box, the above assumptions are not necessary. However, the

analytical determination of the probability of failure of the redundant structure becomes an impossible task, and an empirical study to determine the probable strength must be relied upon.

Based on the previous assumptions, the probability of failure of redundant structure ($P_F[S]$) can be described by the following model, where the failure of a redundant structure requires the failure of all of its elements ($P_F(a_i)$ $i=1, \ldots n$) where n equals the number of non-redundant elements:

$$P_F[S] = P_F(a_1) \cdot P_F(a_2/a_1) \cdot P_F(a_3/a_1a_2) \cdot \ \ldots \ \cdot P_F(a_n/a_1 \ldots a_{n-1})$$

The previous assumptions are necessary so that the terms on the right-hand side of the equation may be defined. That is, the probability of failure of any given element (a_1) depends on the ability to define the probability of exceeding a given load and the probability of exceeding the strength of that element with the given load. Obviously, neither probability can be determined without making the previous assumptions. The assumptions do not imply an exact knowledge of the load and strength in the elements; rather, they imply that the load and strength can be determined within the limits of a range of strength or load with probabilities assigned. Finally, the probability of failure of the element a_1 can be described by:

$$P_F(a_1) = P_E(L_1) \cdot P(s \leq L_1)$$

where $P_E(L_1)$ is the probability of exceeding a given load level L in element a_1 and $P(s \leq L_1)$ is the probability of the strength of element a_1 being less than or equal to L, the given load level.

The second right-hand term P_F (a_2/a_1) and succeeding terms through P_F $(a_n/a_1 \ldots a_{n-1})$ represent the failure of the second through the (n-1)th redundancy on the condition of the failure of the first and each successive redundancy. This conditional dependency must be considered since the probability of failure of element a_2 on the condition of the failure of a_1 $\{P_F(a_2/a_1)\}$ will differ from the probability of failure of a_2 $\{P_F(a_2)\}$ where the change is due primarily to the new load distribution. Reference 3 has demonstrated this dependency.

To demonstrate the analysis model proposed, consider the following example:

A variable mass M is suspended from a fixed surface by three rods, numbered 1, 2, and 3, as shown in Figure 1. Considering loads in the x direction only, this describes a doubly redundant system. The function of this system is the support of the mass and, therefore, failure is described by the inability to suspend the mass any longer. Assuming that the mass M is varied cyclically between O and M_1, the supporting rods 1, 2,

and 3 are subjected to fatigue loading. The probability of failure of the structure may be described by the model as:

$$P_F[S] = P_F(a) \cdot P_F(b/a) \cdot P_F(c/a,b)$$

where the six different failure paths are described by the following rod failure orders:

a	b	c
1	2	3
1	3	2
2	1	3
2	3	1
3	1	2
3	2	1

The structure will fail according to any one of these paths, and most likely according to the path with the highest $P_F[S]$. The computation of the $P_F(a)$, $P_F(b/a)$, and $P_F(c/a,b)$ will be according to the previous equation:

$$P_F(a) = P_E(L_1) \cdot P(s \leq L_1)$$

and subject to the same assumptions.

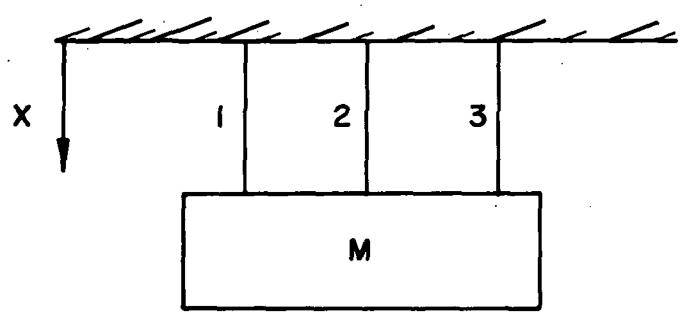

Figure 1. Model of Redundant Structure

It must be observed that these assumptions are rather gross, all-encompassing and, in certain circumstances, invalid. It might be said that the problem has been "assumed out of existence" by these assumptions. However, it can also be said that the assumptions delineate the real problems of analyzing the probability of failure of a redundant structure.

Essentially, the real problem is being able to describe the load and strength of the elements in a redundant configuration and to derive from this information the probability of failure of the configuration. It should be recognized that the load and strength of the redundant components is not always available and that the analysis becomes further complicated by the probable location of the strength and load in the possible spectrum of

strengths and loads. Reference 3 has considered this same example problem (a simple structural configuration) where the load and strength are assumed as known, and has made similar assumptions. The mathematics required to solve even this simple problem become extremely complex, so much so that the application of this analysis to actual structure becomes quite implausible.

2.5.3 Parametric Effects

The effect of the following parameters on the reliability (probability of failure) of redundant structure is discussed.

2.5.3.1 Margin of Safety

The margin of safety in the QSDC Procedure is defined in the same manner as the Present System where the margin of safety is the ratio of the allowable stress to the actual stress at the design condition minus one.

The margin of safety (MS) of the Present System can be described as follows: The design load level (Ultimate) is determined by the loads analysis, which is then multiplied by the factor of safety (FS). The vehicle is, then, sized by determining the proper area (A_D) to produce the allowable stress (F_{all}) given the structure and the factored load. (The FS may be a composite of several FS, i.e., fitting and fatigue FS's.) Thus,

$$P_D = P_u \cdot FS$$

where A_D is chosen such that

$$P_D/A_D = F_{all}$$

$$A_D = \{A_n/(P_D/A_n) = F_{all}\}$$

Assuming that the structure sees an ultimate load, the actual stress in the structure would equal P_u/A_D or

$$f_{act} = P_u/A_D.$$

The margin of safety can then be expressed in terms of the factor of safety as:

$$MS = \frac{F_{all}}{f_{act}} - 1$$

$$= \frac{P_u \cdot FS}{A_D} \cdot \frac{A_D}{P_u} - 1$$

$$= FS - 1$$

As the relationships are similar for the QSDC Procedure, we can express the margin of safety for the Limit and Omega design points as:

$$MS_L = LTFS - 1$$

and

$$MS_\Omega = OTFS - 1$$

As the LTFS and the OTFS are chosen on the basis of reliability, the relationship of the margin of safety to the system reliability becomes obvious. Similarly, the relationship of the margin of safety to the probability of failure is also obvious.

2.5.3.2 Tests

The type and number of tests conducted on the structure have been related to the structural reliability of the design in the designation of the design criteria for the static and fatigue tests. As such, these relations were presented in Sections 2.2.4 and 2.3.4 of Volume II. The QSDC Procedure places the emphasis of structural verification on the loading test of an actual full-scale structure rather than on non-destructive inspection techniques.

2.5.3.3 Periodic Inspections

The periodic inspection of the structure by both visual and non-destructive methods will detect flaws that could produce failure. However, the actual detection of flaws is subjective and strongly dependent on the inspector's interpretation of the available data. As such, it is not necessarily amenable to the determination of the reliability remaining in the structure at any time during the lifetime of the vehicle because cracks can be overlooked. Rather, the purpose of periodic inspection has been the detection of cracks which, if left unattended, would fail the structure before the next inspection. Essentially the period of the inspection becomes the important consideration in determining the required strength for a given component as presented by B. O. Lundberg in several of his papers (References 4, 5, and 6).

2.5.3.4 Fatigue Measurement Techniques

The application of fatigue measurement techniques to the problem of redundant structure would require that the failure process be separated out and analyzed by a cumulative damage theory. This would be consistent with Lundberg's "critical number of parts" criterion. Alternatively, the fail-safe load criterion would not analyze the part-by-part failure of the redundant structure but would associate a fatigue damage index with the fail-safe load level, where degradation of the strength to the fail-safe load level would equal an index of 1 or 100% of allowable fatigue damage. The latter method is discussed in Volume II, Section 2.3.

2.5.3.5 Replacement-Refurbishment Procedures

When used in conjunction with periodic inspections, replacement of fatigue sensitive components effectively increases the reliability of the structure. Essentially the fatigue damage in the component is reduced to zero with the replacement and possibly reduced to some portion of the fatigue damage by refurbishment. For example, the drilling and plugging of a cracked honeycomb panel only eliminates the critical damage in the repaired part of the panel. Damage may have been incurred in other parts of the panel and may have gone undetected; for instance, microscopic cracks which could quickly propagate to failure at another section of the panel. Therefore, the past history of loading in the rest of the panel cannot be ignored in the assessment of the fatigue damage index for the repaired panel (the crack initiation period was completed during the previous loading and the crack propagation phase may be all that remains before structural failure). The ratio of the time of crack initiation in the panel to the panel lifetime (initiation + propagation) is dependent on the configuration of the panel and the crack orientation. The fatigue damage index of a repaired panel may then be typified by the ratio of the propagation phase to the lifetime. Say 20% of the lifetime can be attributed to crack propagation, then the fatigue damage index of the repaired panel would be 0.8. The length of time of these phases will also depend on the loading spectrum and the critical crack length, where the critical crack length could be defined by the fail-safe load level.

3. RELATED TOPICS

During the development of the QSDC procedure, the applicability of reliability, strength, scatter, and yield strength to the space shuttle was discussed. The discussion on reliability relates, in proper perspective, the output of the QSDC Procedure computer programs to the entire structural reliability goal and explains the rationale for using the design factor of safety of a single element for the entire structure. The discussion on strength scatter points out some of the limitations on the data used to estimate the strength scatter values proposed in the Applications Guide and presents general guidelines for selecting the appropriate data. The discussion on yield strength indicated that the QSDC Procedure is readily adaptable to a yield strength requirement. However, the QSDC Procedure does not now include a yield strength criterion since it is based on a probability of failure analysis where failure is defined as catastrophic failure.

3.1 Reliability

3.1.1 Determination of the Structural Reliability

The structural reliability considered in the QSDC Procedure is the ability of the hardware, the flight article, to perform its function without failure for its design lifetime. The structure, as referred to here, is the framework of skin, stringers, frames for the fuselage, wing, tail, landing gear, etc., and is not to be confused with the system, consisting of the structure, the control (pilot, etc.) organization, and the non-structural systems, such as the propulsion system. The structure and system can be further differentiated by their functions, where the function of the structure is to sustain the loads imposed on it by the operational conditions, and the function of the system is the completion of a specified mission. The corresponding reliabilities will also be different as a result of the difference in function: the reliability of the structure is a measure of its ability to sustain the loads without failure, and the reliability of the system is a measure of its ability to complete the mission successfully. The structural reliability is a factor in the system reliability, but is not equivalent to it. When combined with the control system reliability and the non-structural system reliabilities, the structural reliability should produce the system reliability. Whatever the relationship between the structural and system reliabilities is, it is to be considered in the analysis and in the setting of the structural reliability: be it LOW, STANDARD, or HIGH in value. However, the composition of the structural reliability is of concern. As the system reliability consists of the combination of sub-system reliabilities, so the structural reliability consists of the combination of the reliabilities of its components where the reliability of its components is described by the analysis of

the QSDC Procedure as discussed in Section 3.1.2. The relation of these component reliabilities to the structural reliability will be a function of how the components are combined to form the structure. Basically, the structural components can be combined to form a structure in two ways: as members of a determinant structure or as members of a redundant structure. Similarly, there are two ways to combine reliabilities (interpreted here by the complement of the reliability - the probability of failure): as the combination of independent probabilities or as the combination of conditional probabilities. Thus, in the analysis of the reliability of a determinant structure, the combination of independent probabilities would be used. As an example of determinant structure, consider the major elements of an aircraft, namely the wing, tail, and fuselage. Obviously, if the wing, tail, or fuselage fails, the structure fails. By definition of determinant structure, the failure of one element means the failure of the combination of elements, i.e., the structure.

In the case of redundant structure, the conditional probabilities should be used. An example of a redundant structure would be the wing box of an aircraft. The upper and lower surfaces consist of skin, stiffeners, and spar caps. In this case, the failure of the skin, stifferer, or spar cap does not necessarily mean the failure of the combination, i.e., the structure. Therefore, by definition, the structure is redundant. The reliability, or the probability of failure, of the combination is therefore conditional on the failure of some or all of the components. That is, there is a probability of failure of the combination of components, given that one component has already failed. Since the mathematics of independent and conditional probabilities have been worked out and can be found in any good text on statistics, such as References 7, 8, and 9, they need not be discussed here.

3.1.2 Component Reliability

The reliability computed by the QSDC Procedure is the result of a strength-exceeding load analysis. The strength to be used in the analysis is one of the basic strengths, such as tension, compression, bending, torsion, or their combinations, which may be related to an element or combination of elements (component) of the structure. The load used in the analysis is derived from an operational condition and must be referenced to the same element or component whose strength is being considered. Obviously, if the load exceeds the strength, the element or component fails, and the reliability is then zero. However, the analysis is not confined to the discrete single load and strength as in this example, but rather the analysis considers the distribution of possible loads and strengths. Essentially, these distributions must be considered if the probability of failure of any structure is to be accurately computed. Although further details of the probability of failure analysis are given in Reference 1, the point remains that the reliability computed

by the computer program is the reliability of the component of the structure. The reliability of the component required for the total structural reliability should be determined by the relations discussed in Section 3.1.1. When such a determination cannot be made, the structural reliability should be met by each and every component.

The analytical development of the probability of failure, or reliability, has not been considered as feasible because the reliability of the whole is not necessarily the sum of the reliabilities of its parts. If the definition of parts is exclusive of the interaction of the parts, this reasoning is valid. However, if the interaction of the parts is considered in the "summation," then the reliability may be computed by such a summation of parts. The interaction considered is the effect on the probability of failure of a component by the probability of failure of another component.

Obviously, a structure can only fail once, and then only at the component that has been overloaded. It can be concluded, therefore, that the failure of the structure is the result of the failure of a single principal component in its particular failure mode for the given loading condition. If one component is much weaker than the rest, then the structure will fail as a result of that component failing before any other component fails. This is the rationale of the static test; that is, if a component of the structure is weak, it will fail in the test and the weakness will be disclosed. The structure should therefore reflect this situation in the analysis of the probability of failure; that is, the probability of failure of each component is dependent (or conditional) on the probability of survival of the other components, as well as on the probability of failure of its subcomponents (elements). This can be described mathematically, as:

$$P_F[C_1] = P_F\ [C_1/P_S[C_2],\ P_S[C_3],\ \ldots P_S[C_n]\ ]$$

where

$P_F[C_1]$ represents the probability of failure of component 1.
$P_F[C_1/P_S[C_2]\ \ldots\ P_S[C_n]]$ represents the probability of failure of component 1 on the condition of the probability of survival of component 2, etc.
n represents the total number of components.

and

$$P_F[C_1] = P_F[C_1/P_S[C_{11}],\ P_S[C_{12}],\ \ldots P_S[C_{1m}]\ ]$$

where C_{11} represents the subcomponent (element) 1 of component 1, etc.

m - represents the total number of subcomponents of component 1 and combined:

$$P_F[C_1] = P_F\ [C_1/P_s[C_2], \ldots P_s[C_n],\ P_s[C_{12}], \ldots P_s[C_{1m}]\ ]$$

Repeating the same equation for all of the components n, the probability of failure of the structure could be written as the combination of the n components

$$P_F[C_1] = \{P_F[C_1],\ P_F[C_2],\ \ldots\ P_F[C_n]\}$$

where { } denotes the function defining the combination of the components required by the structural configuration (see Section 3.1.1). However, this rather massive and incomprehensible result can be greatly simplified by assuming that the failure of the structure is due to a single component lower in strength than the rest. Essentially, the probability of survival of the rest of the structures would be 1.0, and the results would be

$$P_F[S] = P_F[C_i]$$

where C_i is the understrength component. The rest of the components essentially drop out of the picture. Obviously, the designer must be able to determine which component is the weakest and design it with at least the desired structural reliability so that the entire structure will be reliable. This is the rationale of the QSDC Procedure in choosing the strength scatter of the component with the largest strength scatter (the weakest component) as the strength scatter to be used for the entire structure. The LTFS and OTFS (see Volume II) derived from this scatter will be sufficient for the weakest component and conservative for the remainder of the structure for that loading condition and failure mode.

The probability of failure, hence reliability, of the component will be the result of the several loads and their combinations that are induced on the component by the corresponding operational conditions. Mathematically,

$$P_F[C_1] = P_F[C_1/E_{01},\ E_{02},\ \ldots E_{0k}]$$

where E_{01} represents the exceedance of the operational condition 1.
k represents the number of operational conditions that affect component 1.

Obviously, all the conditions and their combinations must be investigated to define the critical loading conditions of the components. Present knowledge of these conditions and loads and their relations greatly simplify the analysis of the probability of failure of the component.

Finally, the probability of failure analysis also depends on the accuracy of the load analysis. Consideration so far has been given to the strength of the component, but the estimation by the load analysis of the load that the component will experience relative to the operational condition will have an effect on the actual reliability of the component and hence on the reliability of the structure. Unfortunately, there is no way to account for this dependency in the design analysis except to be aware that the reliability indicated by the static test is conditional on the verification of the loads by the flight loads program.

3.2 Additional Strength Requirement - Yield

Yielding has played such an important role in the design of aircraft systems that it has been called the second strength requirement. Essentially, the yield strength requirement is a "no yield at the Limit Load" or a positive yield margin at Limit (Reference 10). The yield strength requirement has been interpreted as "no permanent set" (Reference 10) and "no detrimental permanent deformation" (Reference 11) with regard to the static test to the Limit Load. In these terms, the yield strength requirement has become a practical strength requirement.

The yield strength requirement was not excluded from the QSDC Procedure intentionally: rather, it was excluded because it cannot be defined as failure in the same sense as the catastrophic failure on which the QSDC Procedure is based. Yielding is purely an economic factor. Whenever it occurs the affected structure is replaced and if necessary the new structure is strengthened to avoid future occurrences. The important point here is that the structure still exists and can be restored. If a catastrophic failure occurs, the structure is destroyed, lives may be lost, and the mission is incomplete. Therefore, catastrophic failures must be avoided at all costs, whereas yielding may be tolerated at a reasonable cost. With this difference in mind, the yield strength requirement cannot be incorporated in the probability of failure analysis of the QSDC Procedure. However, since the yield strength requirement should not be ignored, it is suggested that a "probability of yield" analysis be carried out on the structure.

A "probability of yield" analysis would consider the yield strength similarly as the QSDC Procedure considers the failing strength of the structure. For example, the yield strength will exhibit the same sort of distribution as the failing strength, and could be represented by a mean (μ) and a standard deviation (σ). Yield strength scatter coefficients (γ_{Sy}) could therefore be computed from the mean and its standard deviation. These yield strength scatter coefficients could then be associated with appropriate yield factor-of-safety functions (similar to the LTFS of Section 2.2.3, Vol. II). Finally, these yield factor of safety functions can be referenced to the levels of

the "probability of yield" considered acceptable by the designer and program manager.

The "probability of yield" that the designer and program manager will be forced to accept will be much higher than the probability of failure used in the QSDC Procedure. This is not inconsistent with the intention of either the Present System or the QSDC Procedure; rather, it is the reflection of it. Preliminary investigations have indicated that the yield strength scatter is larger than the failing strength scatter for most materials; the mean strength (μ) is lower and the standard deviation (σ) is the same or larger. Assuming that the LTFS relation (Figure 6, Volume II) is used; the larger strength scatter would require a larger factor of safety than specified as the LTFS. Coupling this with the yield strength allowable stress level, which is usually about 66 percent of the failing strength allowable stress, the yield strength requirement would place a much more severe strength requirement on the structure if the same reliability as that for the failing strength is required. As a result, lower levels of reliability or higher "probability of yield" than the probability of failure should be considered. After all, yield is only an economic trade-off and therefore can accommodate such a consideration.

3.3 Strength Scatter

Although the methods of estimating the strength scatter of the structure are discussed in detail in Volume II, Section 3, the limitations on what should be included in the strength scatter estimated from test results are not discussed. That is, what is sufficient to define the strength scatter of the structure is not discussed. The strength scatter has been defined as the variation in failing loads that occur in a group of nominally identical structures that are subjected to the same test conditions. In order to remove the subjective nature in the definition of nominally identical structures and the definition of same test conditions, the following guidelines are presented. First the data and factors that should not be considered in defining a strength scatter are:

1) Failing loads of structures clearly in violation of the specifications for fabrication. An example would be the failure to weld a specified joint, with failure resulting.

2) Failing loads of structures in which wrong material has been substituted.

3) The combinations of first, second, etc., generations of a given structure where the generations are defined by redesign as a result of some failures or testing.

4) The consideration of only a single-producer variation in strength as opposed to the industry-wide variation.

Second, the factors that should be considered in establishing the strength scatter are:

1) The failure mode - all of the test structures or data points must be the result of the same type of failure.

2) The environment - when the atmosphere is contributing to failure (temperature, corrosion) its impact on the data used must be considered.

3) Failing loads of structures with errors that are not clearly in violation of a written specification.

4) The test structures or data is for a single "generation" of the structure considered or a similar structure.

5) The industry-wide variation of the strength of the structure, when possible.

The first two factors not to be considered are representative of the blunders that can occur in initial fabrication or in the service maintenance of the structure. Care should be taken that the failure is attributed to one or the other of the fabrication or maintenance before it is excluded from the strength scatter data. Otherwise it could fall under the jurisdiction of the third factor of those to be considered. The third factor not to be considered and the fourth factor to be considered are opposites. The point behind this consideration is the fact that a redesigned structure is a "new" structure. The "new" structure is based on the design and failure of the original ("old") structure and therefore more is known about the "new" one. Essentially, the inclusion of both the old and "new" structures in the same strength data would deny that any improvement had occurred, thus producing a higher γ_S than actually exists. The last factor to be considered is the industry-wide variation in strength as opposed to the single producer. In the case of basic materials and simple structural elements this consideration can be made. However, when the more complex structural elements such as special forgings and castings, or structural components such as wing boxes are considered, the nominally identical structures may be only those of a single producer.

When insufficient data exists to accurately describe the strength scatter of the structural component (as is presently the case), then an estimation method should be used to determine a strength scatter. Caution must be exercised when the estimation results in a very low strength scatter ($0.01>\gamma_S>0.03$) because the design factors associated with this range of strength

scatter allow little room for error. Therefore, there should be a requirement that the estimated strength scatter be justified. The justification of the strength scatter should be in the form of sufficient tests made prior to the use of the component in service. When the estimation results in higher strength scatter values, the need for justification is less since the design factor will approximate that of the Present System which has proven adequate in the past.

4. CONCLUSIONS

The QSDC Procedure was developed to provide improved methods for designing and utilizing structural systems in the space shuttle. The QSDC Procedure solves the "new design" problem by providing methods to estimate both the strength scatter and the loading spectrum of new structural configurations. This study, therefore, emphasized the prediction, or the estimation, of the strength scatter and the Limit and Omega design levels. Section 3 of Volume II presents techniques to estimate these three variables. The use of the variable values is detailed in Reference 1 and repeated briefly in Section 2, Volume II.

After defining the failure of a redundant structure, this study demonstrated how the structural margins of safety, tests, periodic inspections, fatigue measurement techniques, and replacement and/or refurbishment procedures could be successfully related to system fail-safe requirements and to the QSDC parameters that aid in describing their effect on the probability of failure. These relationships are discussed in Section 2.5 of this volume.

5. RECOMMENDATIONS

Based on the experience gained during the present contract, the following recommendations are made with respect to the future development of the QSDC Procedure, the incorporation of reliability procedures in the space shuttle design, and the further investigation of the strength scatter coefficient of materials.

5.1 Follow-On Plan

Before specific steps for an immediate course of follow-on action can be recommended, a general statement of the intended overall plan for the development of the QSDC Procedure should be stated: The overall plan for the development of the QSDC Procedure is to establish it as a useful structural design criteria method that can be utilized as an acceptable option to the present structural design criteria methods. Thus, the purpose of the recommended follow-on plan will be to achieve this goal, and the specific steps will outline the course of action necessary to achieve this goal. Specific steps will be necessary in essentially two areas: the first of which this section will discuss and the second, the demonstration of the QSDC Procedure relative to a specific structure, will be discussed in the next section. The first area in which the QSDC Procedure requires further study is in the specific criteria fields of:

1) a yield strengh requirement
2) the definition of critical flight situations
3) the determination of stability factors
4) the determination of dynamic factors

Study is necessary to establish the utility of the QSDC Procedure in these areas since they have not been previously investigated. Essentially the scope of the QSDC Procedure as a design criteria methodology must be defined. Once this scope is defined, its application can be pursued.

As the breakdown of how the study should be conducted in each subject area is similar, the study on the yield strength requirement is explained as an example. The study can be divided into a five-task effort, as follows:

Task	Description
1)	Review the State of the Art of Yield Strength Criteria.
2)	Survey of Yield Strength Data to Establish Strength Scatter Values.
3)	Development of Reliability of Present Yield Strength Criteria.
4)	Development of Yield Strength Design Factors and their Relationship to Reliability.
5)	Specification of Guidelines for Using Statistical Yield Strength Criteria.

Under Task 1 the Air Force, Navy, and industry will be interviewed on the current practice in yield strength criteria, interpretation, implementation, and verification. From this review, a proper characterization of present practice can be made, and the areas where the QSDC Procedure can benefit the design process can be defined.

Task 2 would, essentially, be comparable to the strength scatter investigation carried out for ultimate strength. Data on all levels of structural configurations will be gathered and analyzed for the strength scatter coefficient at yield.

Task 3 would utilize the strength scatter for yield information in a program to determine the "yield reliability" of the current airframe systems.

Assuming that the relation of criteria to reliability is best characterized by yield strength design factors, Task 4 will develop the relationship of design factors to reliability and put it in a criteria format.

Task 5 calls for proper documentation of the statistically based yield strength criteria with guidelines for its proper use.

In summary, the above describes what should be investigated to further develop the QSDC Procedure and how it should be investigated as a follow-on to the current contract.

5.2 Application to Design of Phase C Structural Component

The second major area in which the development of the QSDC Procedure should be made is in the demonstration of its practicality. It is recommended that the QSDC Procedure be implemented in a parallel study with the Present System in the design of the Phase C space shuttle structural component. Such a study is recommended so that the benefits of the QSDC Procedure can be properly illustrated. The actual benefits of the use of the QSDC Procedure cannot often be realized in a general type study such as that in the present contract, but are clearly defined in a structural application.

5.3 Strength Scatter Investigation

The strength scatter data of Section 2.4, Volume II, represents what was available and could be included in the amount of time the program allowed. The data presented is only the beginning of the data that could be obtained by a more extensive program in this area. Such a program might include an effort to include the strength scatter coefficient on the MIL-HDBK-5A Coordinating Committee Agenda. If the strength scatter were considered by this committee as an important material parameter, it might eventually be included in the handbook. As previously noted, there is a good deal of data available from this committee. The inclusion of this data could greatly assist in the development of the QSDC Procedure.

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